

# On the Origin of Globular Clusters in Elliptical and cD Galaxies

Duncan A. Forbes

*Lick Observatory, University of California, Santa Cruz, CA 95064*

and

*School of Physics and Space Research, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*

*Electronic mail: forbes@lick.ucsc.edu*

Jean P. Brodie

*Lick Observatory, University of California, Santa Cruz, CA 95064*

*Electronic mail: brodie@lick.ucsc.edu*

Carl J. Grillmair

*Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109*

*Electronic mail: carl@grandpa.jpl.nasa.gov*

## ABSTRACT

Perhaps the most noteworthy of recent findings in extragalactic globular cluster (GC) research are the multimodal GC metallicity distributions seen in massive early-type galaxies. We explore the origin of these distinct GC populations, the implications for galaxy formation and evolution, and identify several new properties of GC systems. First, when we separate the metal-rich and metal-poor subpopulations, in galaxies with bimodal GC metallicity distributions, we find that the mean metallicity of the metal-rich GCs correlates well with parent galaxy luminosity but the mean metallicity of the metal-poor ones does not. *This indicates that the metal-rich GCs are closely coupled to the galaxy and*

*share a common chemical enrichment history with the galaxy field stars.* The mean metallicity of the metal-poor population is largely independent of the galaxy luminosity. Second, the slope of the GC system radial surface density varies considerably in early-type galaxies. However the galaxies with relatively populous GC systems for their luminosity (called high specific frequency,  $S_N$ ) *only* have shallow, extended radial distributions. *A characteristic of high  $S_N$  galaxies is that their GCs are preferentially located in the outer galaxy regions relative to the underlying starlight.* Third, we find that the ratio of metal-rich to metal-poor GCs correlates with  $S_N$ . In other words, *high  $S_N$  galaxies have proportionately more metal-poor GCs, per unit galaxy light, than low  $S_N$  galaxies.* Fourth, *we find steeper metallicity gradients in high  $S_N$  galaxies.* This is due to the greater number of metal-poor GCs at large galactocentric radii.

We critically review current ideas for the origin of GCs in giant elliptical (gE) and cD galaxies and conclude that the gaseous merger model of Ashman & Zepf (1992) is *unlikely* to account for the GC systems in these galaxies. Tidal stripping of the GCs from nearby galaxies appears to contribute to the GC population in the outer parts of cD galaxies, but we suggest that the vast majority of GCs in gE and cD galaxies have probably formed *in situ*. We speculate that these indigenous GCs formed in two distinct phases of star formation from gas of differing metallicity, giving rise to the bimodal GC metallicity distributions. The metal-poor GCs are formed at an early stage in the collapse of the protogalactic cloud. The metal-rich GCs formed out of more enriched gas, roughly contemporaneously with the galaxy stars. *In this sense the metal-rich GCs in elliptical galaxies are the analog of the metal-poor halo GCs in spirals.* The disk GCs in spirals may represent a third phase of this formation process.

## 1. Introduction

Globular clusters have long been recognized as ‘galactic fossils’ and like their counterparts in palaeontology they provide a unique tool for studying galaxy formation and evolution at early times. In particular, they may provide the best probe of chemical enrichment and star formation in the initial stages of galaxy formation. Observations of globular clusters (GCs) may enable us to distinguish between variants of the collapse and merger models for elliptical galaxy formation, a distinction that has been difficult to make in the past (Kormendy 1990).

The first step in using GCs to probe galaxy formation is to understand the formation of GCs themselves. A variety of models (e.g. Fall & Rees 1985; Murray & Lin 1992; Kumai, Basu & Fujimoto 1993a; Harris & Pudritz 1994; Vietri & Pesce 1995) have sought to explain the formation mechanism for GCs. These models focus on gas cloud physics, including metallicity, cooling and star formation rates, shocks etc. Although many of the early models have been ruled out, some of the more recent models may eventually be accepted as a prescription for GC formation. In this paper we take a different approach, and attempt to determine where and when GCs formed by examining the systemic properties of GC systems. This may provide constraints for the further refinement of the GC and galaxy formation models.

The number of GCs in an early-type galaxy scales roughly with the parent galaxy’s luminosity. A useful convention is to normalize the GC counts per absolute luminosity of  $M_V = -15$  (Harris & van den Bergh 1981). The resulting ‘specific frequency’,  $S_N = N \times 10^{0.4(M_V+15)}$ , is probably a measure of GC for-

mation efficiency. When normalized in this way,  $S_N \sim 5$  for most early-type galaxies with magnitudes  $-19 > M_V > -22$  (e.g. Kissler-Patig 1996). However, for  $-22 > M_V > -23.5$  several galaxies have  $S_N \sim 15$  i.e., a factor of three times as many GCs per starlight as ‘normal’  $S_N$  galaxies. Furthermore, these galaxies do not simply have higher global  $S_N$  values but they show evidence for high  $S_N$  values at *all* galactocentric radii (McLaughlin, Harris & Hanes 1994). Finding an explanation for the ‘high’  $S_N$  GC systems has been described by McLaughlin *et al.* (1994) as “the most outstanding problem in globular cluster system research”. The origin of these GC systems has yet to be clearly identified and indeed the question of whether they are anomalous or merely represent the extreme of some distribution has been the subject of debate.

Environmental effects on GC systems have been suspected for some time (e.g. cluster ellipticals have on average higher  $S_N$  values than field ellipticals; Harris 1991). However it was generally believed that there were no correlations between the properties of a GC system and the characteristics of the cluster of galaxies in which the parent galaxy resided (McLaughlin *et al.* 1994). Initial evidence that such correlations did in fact exist was presented by West *et al.* (1995). More recently, based on a larger and more homogeneous sample than was previously available, Blakeslee (1996) has shown that  $S_N$  is correlated with cluster velocity dispersion, the local density of bright galaxies and X-ray temperature. His sample, of 5 cDs and 14 giant ellipticals (gEs), cover the whole range from  $S_N \sim 4$  to  $\sim 10$ . Therefore, although cD galaxies have undoubtedly had more complex evolutionary histories than gEs, their GC systems may actually have had a similar origin.

Blakeslee concluded that bright central galaxies with high  $S_N$  values (these are usually but not always cDs) are not ‘anomalous’ in the sense that they have too many GCs for their luminosity. Rather, these galaxies are ‘under-luminous’ for their clustercentric position and the number of GCs more accurately reflects the local cluster mass density. The fact that there is never more than one massive high  $S_N$  galaxy per cluster is consistent with these findings.

In this paper we focus on the origin of GCs in massive early-type galaxies (i.e. gE and cD galaxies). These galaxies contain the most populous GC systems; which are often the best-studied. Their GCs may have had a similar origin and the galaxies themselves share some common properties e.g., the main bodies of cD galaxies have a similar fundamental-plane relation to that of elliptical galaxies (Hoessel, Oegerle & Schneider 1987). First, we present several recent developments in the study of GC systems that provide important constraints on the origin of GCs. Second, we discuss these results within the framework of various models proposed to explain the properties of GC systems of early-type galaxies. Third, we present our views and supporting data for what we believe are the most viable formation mechanisms (i.e. tidal stripping and *in situ* GC formation). Fourth, we present a case study of the cD galaxy NGC 1399 and the Fornax cluster of galaxies. Finally, we summarize our preferred scenario for the origin of GCs and make several predictions to test these ideas.

## 2. Recent Developments in Extragalactic Globular Cluster Studies

In this section we highlight several aspects of GC systems that have recently been discov-

ered or confirmed. They provide important constraints on any model for GC formation. We have taken distance moduli and the number of GCs ( $N_{GC}$ ) directly from the McMaster Catalog (Harris 1996). The one exception is NGC 1404, for which we take  $N_{GC}$  from the recent HST study of Forbes *et al.* (1997), i.e.  $N_{GC} = 620 \pm 130$ . We believe this to be more accurate than the number quoted by Harris (1996), i.e.  $950 \pm 140$  (see also section 3.5). Extinction-corrected V magnitudes come from Faber *et al.* (1989) and are generally within a few tenths of those given in the RC3. The one exception here is NGC 3311, in which the values are  $V_T^0 = 10.14$  (Faber *et al.* 1989) and  $V_T^0 = 11.16$  (RC3). In a photometric study of the Hydra cluster, Hamabe (1993) finds  $V_T^0 = 10.75$  which is roughly the average of the above two values. Here we adopt the Hamabe value which gives  $M_V = -22.7$ . Most of the galaxies discussed in this section are luminous gE or cD galaxies. In this sense they are generally boxy, slow rotators with shallow central cusps (e.g. Faber *et al.* 1996; Carollo *et al.* 1997). We assume  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

### 2.1. Multimodal Globular Cluster Metallicity Distributions

Although the initial evidence for multimodal GC color (metallicity) distributions in early-type galaxies was weak, there are now a handful of convincing cases (see Table 1 for a summary). The existence of multimodal GC metallicity distributions suggests that GCs have formed in distinct star formation episodes from different metallicity gas; a single star formation episode would give rise to a unimodal distribution. The observed metallicity distributions effectively rule out a simple monolithic collapse and pro-

vide a strong constraint for any GC formation model. The data for 11 gE/cD galaxies from the literature are summarized in Table 1. For NGC 1399 and NGC 4486 (M87) there have been claims for a trimodal metallicity distribution. In these cases we will refer to the metal-poor, intermediate metallicity and metal-rich GC populations. The difference between the metallicity of the metal-rich and metal-poor peaks has a mean value and statistical error of  $\Delta[\text{Fe}/\text{H}] = 1.0 \pm 0.1$  dex.

The metallicity distributions quoted in Table 1 are, strictly speaking, ones of color. The bimodal colors represent GC populations that have different metallicities or ages, or some combination of both. This is the well-known age-metallicity degeneracy that affects the interpretation of optical colors. If we assume that the two populations have the same metallicity and that the red population is very old (i.e. 15 Gyr), then for a typical color difference of  $\Delta(V-I) \sim 0.2$ , the blue population is younger by  $\sim 13$  Gyr. On the other hand, for contemporaneous populations  $\Delta(V-I) \sim 0.2$  indicates that the red population is more metal-rich than the blue one by  $\sim 1$  dex in metallicity. The latter appears much more reasonable given, for example, our knowledge of the Milky Way GC system. In the discussion below we will assume that GC colors mostly reflect GC metallicity but in reality there will probably be some component due to age effects (see also Zepf 1996). For example, Chaboyer *et al.* (1992) have derived an age-metallicity relation for Milky Way halo GCs in which GCs with  $\Delta[\text{Fe}/\text{H}] = 1$  dex are separated in age by  $\sim 4$  Gyrs. High signal-to-noise spectra of a sample of blue and red GCs in an elliptical galaxy are needed to further investigate this issue.

If the characteristics of the GC system in

NGC 4472 (Geisler, Lee & Kim 1996) can be extended to other galaxies, then we can explain the long-standing observation that the mean metallicity of GCs is about 0.5 dex lower than field stars in gEs (e.g. Harris 1991). This then simply arises because the metal-rich GCs have a similar metallicity to the galaxy stars, and the metal-poor GCs are about 1 dex more metal-poor. With a similar number of GCs in each subpopulation, the *mean* offset between GCs and field stars is 0.5 dex, as is generally observed. The lowest luminosity galaxy in Table 1 has  $M_V = -21$ . Less luminous ellipticals with  $M_V > -21$  also show a metallicity offset between GC and galaxy stars (Forbes *et al.* 1996).

In terms of the number of GCs observed with high quality CCD photometry, the best studied GC system is that of NGC 4472 (M49) in Virgo (Geisler *et al.* 1996). Although it is not a high  $S_N$  galaxy ( $S_N = 5.5 \pm 1.7$ ), it is a giant elliptical ( $M_V = -22.7$ ) that is somewhat more luminous than NGC 4486 (M87). Several interesting results were found by Geisler *et al.* which may also hold true for other ellipticals with bimodal metallicity distributions. The two metallicity peaks in NGC 4472 are located at  $[\text{Fe}/\text{H}] = -1.25$  and  $-0.05$ , so that  $\Delta[\text{Fe}/\text{H}] = 1.2$ . They can be well represented by two Gaussians, both with the same dispersion of 0.38 dex, with about 2/3 in the metal-poor peak and 1/3 in the metal-rich peak. (As given in Table 1, for a total population of 6300 this indicates there are about 4200 metal-poor and 2100 metal-rich GCs in NGC 4472.) The overall radial metallicity gradient of the GC system is almost entirely due to the changing relative mix of the two populations with radius. There is little or no evidence for a metallicity gradient within either GC subpopulation

suggesting a largely dissipationless formation process (similar to the halo of our Galaxy). The mean metallicity of the metal-rich population closely matches the underlying field star metallicity over a wide range in galactocentric radius. The metal-poor GCs are simply offset from the field stars by 1.2 dex. The metal-rich GCs are more centrally concentrated than the metal-poor GCs, and have effective radii of  $227''$  and  $274''$  respectively. The galaxy itself has an effective radius of about  $100''$  (Bender, Burstein & Faber 1992).

## 2.2. The Globular Cluster Metallicity – Galaxy Luminosity Relation

A relationship between GC mean metallicity and parent galaxy luminosity (Z–L) was first suggested by van den Bergh (1975) and later supported by the spectroscopic metallicity data of Brodie & Huchra (1991). The existence of this relation, at least for low luminosity galaxies, was disputed by Ashman & Bird (1993). They claimed that the GC metallicity was independent of galaxy luminosity. Larger galaxy samples (Durrell *et al.* 1996; Forbes *et al.* 1996) have now confirmed that such a relationship of the form  $Z \propto L^{0.4}$ , does indeed exist, over 10 magnitudes. The slope of the relation is the same as the galaxy Z–L relation (Brodie & Huchra 1991). Taken together these results indicate that GCs have had a similar chemical enrichment history to their parent galaxy. The Z–L relation holds important clues about GC and galaxy formation processes, but the large scatter, which may be mostly observational error, makes it difficult to reach any definitive conclusions.

In the previous studies of the GC Z–L relation, the GC metallicity was taken to be the mean of the entire GC system. We now know that in several cases, the GC system is

better represented by two GC mean metallicities corresponding to the metal-rich and metal-poor subpopulations. Although observational errors may dominate, there are other reasons for expecting some scatter in the Z–L relation. In particular, some of the scatter will be due to changing proportions of the metal-poor and metal-rich GC populations from one galaxy to the next, which is further complicated by observations that cover different galactocentric radii (metal-poor GCs are more radially extended than the metal-rich ones). In Fig. 1 we plot the mean metallicity of the two subpopulations, listed in Table 1, against the galaxy luminosity. We have assumed errors of  $\pm 0.1$  for Washington color photometry,  $\pm 0.15$  for B–I and  $\pm 0.25$  for V–I colors which reflect the scatter in the color–metallicity relations. A weighted fit for the metal-rich GC peak gives  $[\text{Fe}/\text{H}] = -0.21 (\pm 0.06)$   $M_V - 4.6 (\pm 1.4)$ . The scatter of the metal-rich data points about the relation is less than the estimated error bars, suggesting that our assumed metallicity errors are overestimated. In the lower panel, for the metal-poor GCs, we have simply offset the metal-rich relation downward by  $\Delta[\text{Fe}/\text{H}] = 1.0$  dex (i.e. the average metallicity difference between the two peaks). There is considerably more scatter in the Z–L relation for the metal-poor data points. This is unlikely to be caused by errors or calibration problems and so the difference in scatter must be a real effect. Either there is virtually no Z–L relation for metal-poor GCs or there is a ‘second parameter effect’ causing the significant scatter. Figure 1 clearly indicates that  $[\text{Fe}/\text{H}]$  for the metal-rich GCs is more closely coupled to the luminosity of the galaxy than for the metal-poor GCs. This result will be discussed further in section 3.4.

### 2.3. The Spatial Distribution of Globular Clusters

It has been known for sometime that the radial distribution of GCs is often more extended than the starlight of the parent galaxy (see Harris 1991 for a review). The GC radial surface density profile is usually fit by:

$$\rho = \rho_o r^\alpha$$

where  $\alpha$  is the radial slope. Kissler-Patig (1996) has collected measurements of  $\alpha$  from the literature. After excluding the S0 galaxies, we show in Fig. 2 this slope versus the  $S_N$  value as given by Kissler-Patig. This figure shows that low  $S_N$  galaxies have a wide range of GC radial slopes, whereas high  $S_N$  galaxies *only* have relatively flat slopes. For  $S_N > 7$  the mean slope is  $\alpha = -1.43 \pm 0.12$  (statistical error) and for  $S_N \leq 7$  it is  $\alpha = -1.76 \pm 0.09$ . There are no cases known of high  $S_N$  galaxies with steep GC radial slopes. This ‘zone of avoidance’ is unlikely to be due to selection effects as high  $S_N$  galaxies have numerous GCs and so are relatively easy to find and study. Thus another property of high  $S_N$  galaxies is that their GC systems have a very extended spatial distribution (see also Kaisler *et al.* 1996).

A more useful quantity to examine would be the difference between the GC radial slope and the underlying starlight slope. Unfortunately, the starlight slopes have only been measured over similar galactocentric radii for a handful of galaxies. In the inner (i.e.  $r^{1/4}$ ) regions of cD galaxies, the GC system is generally flatter than the galaxy starlight (Harris 1991; McLaughlin, Harris & Hanes 1993). In other words, a characteristic of high  $S_N$  galaxies is that their GCs are preferentially located

at large radii in the main body ( $r^{1/4}$  part) of the galaxy. In NGC 4486 (M87) the GC radial profile shows evidence for a change in slope at the radius of the cD envelope (e.g. McLaughlin *et al.* 1993). This suggests that the outer GCs and the envelope of cD galaxies have a similar origin. As cD envelopes are generally thought to be a product of their cluster environment (e.g. Kormendy & Djorgovski 1989) this implies that GCs in the envelope<sup>(1)</sup> are also associated with some aspect of the cluster.

### 3. Models for the Origin of Globular Clusters in gE and cD Galaxies

Fall & Rees (1988) characterized GC formation models into three types – primary, secondary and tertiary. In the primary formation models, GCs may form well before the galaxy. In secondary formation models, GCs form at essentially the same time as the galaxy itself, and for tertiary formation models, GCs form after most of the parent galaxy has formed. Given the numerous correlations between GCs and their parent galaxy (see Harris 1991) and the absence of dark matter in GCs, formation well before the galaxy itself (e.g. Peebles & Dicke 1968) and GC formation that is unrelated to galaxies (e.g. West 1993) seems to be ruled out. Theories for the formation of galaxies have traditionally been divided into the ‘collapse’ or the ‘merger’ picture. The present majority view is that both collapse and the merging of subunits (hierarchical clustering) play a role in the formation and subsequent evolution of early-type galaxies. The presence of more than one population of GCs in massive early-type galaxies effectively rules out a simple monolithic collapse. Either the collapse was more complex (e.g. episodic) or some tertiary GC process has occurred (e.g. the accretion of existing

GCs or the creation of new GCs in a gaseous merger).

Below we discuss specific models for the origin of GCs in giant elliptical and cD galaxies: 1) a gaseous merger; 2) cooling flows; 3) intracluster globular clusters; 4) *in situ* GC formation and 5) tidal stripping of GCs from nearby galaxies. The merger model of Ashman & Zepf (1992) and Zepf & Ashman (1993), makes detailed predictions for GC system formation on a macroscopic level which are tested below. Most other models have not made such clear predictions and can therefore only be discussed on a more qualitative basis.

### 3.1. The Gaseous Merger Model

Van den Bergh’s (1984) argued against the merger hypothesis on the grounds that ellipticals have many more GCs per unit light than spirals. An additional problem is that a purely stellar merger of *two* ellipticals (in which no new GCs are created) cannot explain the ratios of metal-poor to metal-rich GCs. In particular, the GC metallicity – galaxy luminosity relation suggests that the metal-poor GCs would come from the lower luminosity progenitor and would therefore also be fewer in number. Column 9 of Table 1 shows that this is generally not the case, i.e. the number of metal-poor GCs exceeds the number of metal-rich GCs. The GC metallicity – galaxy luminosity relation also suggests that metal-rich (luminous) ellipticals are *not* made by simply merging several metal-poor ellipticals. These issues and others have been discussed by van den Bergh (1990).

Schweizer (1987) has suggested that new GCs are created from the gas of the merger progenitors. For a gaseous merger, the models of Kumai, Basu & Fujimoto (1993a,b) propose that GCs form in the collision of high

velocity gas. Their models predict a mass-metallicity relation for individual GCs which is not supported by the observational data (see e.g. Forbes, Brodie & Huchra 1996). Furthermore, this model can not apply to the GC systems of dwarf galaxies which would probably be disrupted by high velocity collisions.

Another merger model that has been the focus of much attention is that of Ashman & Zepf (1992) and Zepf & Ashman (1993). Below we discuss this model in detail in the context of GC formation in gE and cD galaxies. In their model the bimodal GC metallicity distributions are due to the presence of metal-poor GCs from the progenitor spirals and metal-rich ones created from the gas of the merged galaxies. The metal-rich GCs are observed to be more centrally concentrated than the metal-poor ones, as expected in their model. One of the most noteworthy successes of this model is the discovery of protoglobular clusters in currently merging galaxies (e.g. Whitmore *et al.* 1993; Schweizer *et al.* 1996). The sizes, magnitudes, colors and mass distribution of the identified objects generally appear to be consistent with the properties of protoglobular clusters. Although some issues remain (such as destruction of the very low mass objects) it seems plausible that these objects will evolve into *bona fide* GCs. Thus the Ashman & Zepf (1992) model appears consistent with the observations of GCs in currently merging galaxies.

Here we are interested in the origin of GCs in the most massive early-type galaxies. In the framework of the Ashman & Zepf (1992) hypothesis the gEs have been formed by massive gas-rich galaxies or several  $\sim L^*$  galaxies. For cD galaxies they advocate multiple mergers which in turn leads to several “different epochs of [globular] cluster formation and



thus a spread in cluster ages”. Can a gaseous merger and subsequent GC formation, as described by Ashman & Zepf (1992), account for the properties of GC systems in gE and cD galaxies ?

Previous studies of high  $S_N$  galaxies (McLaughlin *et al.* 1994) and brightest cluster galaxies (Blakeslee 1996) have mentioned some problems in trying to account for the populous GC systems with the Ashman & Zepf (1992) merger model. The case of NGC 3311 provides a particularly strong constraint for any GC formation model as its GCs are relatively metal-rich with peaks at  $[\text{Fe}/\text{H}] = -0.5$  and  $+0.15$  (Secker *et al.* 1995). It is hard to see how the GCs in a spiral galaxy (which typically have mean  $[\text{Fe}/\text{H}] = -1.5$ ) can account for the ‘metal-poor’ peak of  $[\text{Fe}/\text{H}] \sim -0.5$ . Here we detail some of the observational data which are contrary to the expectations of the Ashman & Zepf (1992) merger model, in decreasing order of significance.

- **The metal-poor GCs are more numerous than the metal-rich population.** In order to explain high  $S_N$  galaxies by the merger of several normal  $S_N$  galaxies, the majority of GCs must be created in the merger event. This implies that the metal-rich GCs should be more numerous (by a factor of  $\sim 3\times$ ) than the metal-poor GCs. This is not the case. In Table 1 we give the ratio of the number of metal-rich to metal-poor GCs (this is equivalent to  $\Delta S = N_{\text{new}}/N_{\text{old}}$  as defined by Ashman & Zepf 1992). This ratio is expected to vary from  $\sim 1$  for normal  $S_N$  ellipticals to 4 for high  $S_N$  galaxies. Table 1 shows that this ratio (column 9) is generally less than 1. Furthermore, in the merger model this ratio should increase with increasing  $S_N$  as larger numbers of new (metal-rich)

GCs are formed. Instead we find that it *decreases*, as shown in Fig. 3. Thus a property of high  $S_N$  galaxies is that they have relatively more metal-poor GCs, in direct contradiction to that expected in the Ashman & Zepf (1992) model. For the cD galaxies in Table 1 the number of metal-poor GCs significantly exceed the metal-rich ones.

- **The radial metallicity slope increases with  $S_N$ .** Zepf & Ashman (1993) predict that the “colour [metallicity] gradients of ellipticals with high  $S_N$  values will be shallower than those with normal  $S_N$  values”. This would be so because in a high  $S_N$  galaxy, large numbers of metal-rich GCs should be formed near the center and the metal-poor GCs would be ‘puffed up’ to large galactocentric radii (see Zepf & Ashman 1993). We have collected metallicity gradients and  $S_N$  values from the literature and listed them in Table 2. In Fig. 4 we plot the  $[\text{Fe}/\text{H}]$  metallicity gradients versus  $S_N$ . Although there is considerable scatter, the trend is for high  $S_N$  ellipticals to have *steeper* metallicity slopes than normal  $S_N$  ellipticals. This trend is in direct contradiction to the Zepf & Ashman (1993) prediction and appears to be a general problem for the merger model. Geisler *et al.* (1996) found that the merger model prediction failed to match the observed GC metallicity in both absolute value and radial variation for NGC 4472.

We have made a crude prediction for the variation of metallicity slope with increasing  $S_N$  based on the data for NGC 4472 (Geisler *et al.* 1996). As appears to be the case for NGC 4472 (M49), we will assume that the observed GC metallicity gradients in ellipticals are due solely to the changing relative mix of metal-rich and metal-poor GCs. Fur-

thermore, we will assume that the only difference between a galaxy of  $S_N = 5.5$  (i.e. NGC 4472) and one with  $S_N = 11$  is an increase in the number of metal-poor GCs (i.e. the number of metal-rich GCs remains constant). Thus we can predict the metallicity slope of a galaxy with  $S_N = 11$ . If these additional GCs are distributed with the same surface density distribution as is currently seen, then we expect a metallicity gradient of  $\Delta[\text{Fe}/\text{H}]/\Delta\log R = -0.58 \text{ dex}''$ . The dashed line shown in Fig. 4 simply connects the data point for NGC 4472 (i.e  $S_N = 5.5$  and  $\Delta[\text{Fe}/\text{H}]/\Delta\log R = -0.41$ ) to that expected for an  $S_N = 11$  galaxy with a metallicity gradient of  $-0.58$ . It reproduces the general trend surprisingly well. Note that the Ashman & Zepf (1992) predicted relation would have a gradient of the opposite sign to this line.

- **High  $S_N$  galaxies do not have peaky central GC densities.** The gas in a merger quickly dissipates to the galaxy center, where large numbers of new GCs should form. The expected higher GC surface densities in the centers of high  $S_N$  galaxies are *not* seen. In fact the surface density flattens off in log space giving a GC system ‘core’ (e.g. Grillmair, Pritchet & van den Bergh 1986; Lauer & Kormendy 1986; Grillmair *et al.* 1994a). The size of this core is larger in more luminous galaxies and this does not appear to be due to destruction effects over time (Forbes *et al.* 1996).

- **Multiple mergers will not produce distinct metallicity peaks.** Based solely in luminosity terms, roughly  $10 L^*$  galaxies would be required to form a cD galaxy or the more massive ellipticals, from multiple mergers. In general these galaxies will have slightly differ-

ent GC mean metallicities and the gas (from which new GCs form) should be enriched by varying amounts. Therefore, unless all of the merging galaxies are similar, we would expect a broad, top-hat type distribution covering a range of metallicity, but instead distinct metallicity peaks are seen. In the case of NGC 4472 (although not a cD it has a similar luminosity to a cD galaxy) the metal-rich and metal-poor peaks have a similar dispersion when fitted with a Gaussian.

- **Galaxies with the same luminosity should have similar  $S_N$  values.** If galaxies are made from multiple mergers, why do some apparently create GCs much more efficiently than others? For example, NGC 4486 (M87) and NGC 4472 (M49) both lie in the Virgo cluster and have essentially the same luminosity, and yet they have quite different  $S_N$  values (13 and 5.5 respectively). In the merger hypothesis, this would indicate that the GCs in NGC 4486 formed  $\sim 3\times$  more efficiently than those in NGC 4472.

- **The GC surface density profiles of normal  $S_N$  galaxies are not always flatter than the underlying starlight.** Zepf & Ashman (1993) “expect the globular cluster system to be noticeably flatter than the galaxy” for normal (i.e. not high  $S_N$ ) galaxies. As shown in Fig. 2, galaxies with  $S_N \leq 7$  have a wide range in GC surface density slopes suggesting a wide range in the difference between GC and starlight slopes. Kissler-Patig *et al.* (1996) have studied several galaxies in the Fornax cluster with  $S_N < 7$ . All have GC slopes that are consistent with the starlight slope – *none* are noticeably flatter contrary to the prediction of Zepf & Ashman (1993).

• **The main body and envelope of cD galaxies appear to be distinct.** For high  $S_N$  galaxies, Zepf & Ashman (1993) predict in general that “the properties of the galaxy and the globular cluster system should be similar”. Both the main body and the cD envelope should be formed by the same mergers. In practice, the envelopes of cD galaxies are generally found to be structurally distinct from the rest of the galaxy (e.g. Mackie 1992). Furthermore, in both NGC 1399 and NGC 4486 (M87) the velocity dispersion of the GCs is well in excess of the stellar velocity dispersion at large radii (Grillmair *et al.* 1994b; Huchra & Brodie 1987; Mould *et al.* 1990); for NGC 1399 the GC velocity dispersion in the cD envelope is close to that for the galaxies in the cluster.

To summarize, the gaseous merger model as proposed by Ashman & Zepf (1992) for GC formation in massive early-type galaxies faces some serious difficulties. We note that some of these difficulties have been identified by Ashman & Zepf (1997) and possible solutions suggested. However it is our view that the disagreements between the observational data and the expectations from the Ashman & Zepf merger model are still substantial. In particular, the model cannot explain the large numbers of excess GCs present in high  $S_N$  cD galaxies and appears to be in conflict with GC trends in normal  $S_N$  giant ellipticals.

An open question is whether the Ashman & Zepf (1992) model can explain the origin of GCs in *low* luminosity ellipticals. It is currently not clear whether such galaxies are smaller versions of gEs or if they form a distinct population (e.g. Carollo *et al.* 1997). Using the list of Kissler-Patig (1996), we find ellipticals with  $-19.5 > M_V > -21.0$  have  $S_N$

$= 4.6 \pm 0.7$ . Whitmore *et al.* (1997) show that in the best-studied merging galaxies the number of new GCs created is equal to or less than the number of original GCs from the progenitor spirals. This means that the  $S_N$  values, after 15 Gyrs, are  $\sim 2-3$ . Globular clusters need to form with much higher efficiency in a gaseous merger if the  $S_N$  values of merger remnants are to match those of elliptical galaxies. So the argument that there are too many GCs in ellipticals to be explained by mergers (van den Bergh 1984) may still be valid. If the GC systems of low luminosity ellipticals are not the result of a merger, then currently merging galaxies must form a galaxy with characteristics different from today’s ellipticals (see also van den Bergh 1995).

### 3.2. Cooling Flows

It has been suggested that GCs could form in the material that cools and condenses from cluster-wide hot gas (Fabian *et al.* 1984). Richer *et al.* (1993) proposed that the protoglobular clusters seen in NGC 1275 were the result of the  $\dot{M} \sim 300 M_\odot \text{yr}^{-1}$  cooling flow. Subsequently, protoglobulars have been identified in several galaxies without cooling flows (e.g. Whitmore *et al.* 1993, 1997; Schweizer *et al.* 1996). Bridges *et al.* (1996a) have discussed cooling flow GC formation and concluded that “it seems most unlikely that cooling flows are responsible for the high  $S_N$  phenomenon”. Similar views were put forth by Grillmair *et al.* (1994b) and Harris, Pritchet & McClure (1995). We refer the reader to these works for further details.

### 3.3. Intracluster Globular Clusters

West *et al.* (1995) proposed that there exists a population of GCs that are associated with the potential well of the cluster

of galaxies rather than with any individual galaxy. A trend for the number of GCs to correlate with X-ray temperature (once corrected for the distance of the galaxy from the dynamical center of the cluster) was taken as evidence in favor of their intracluster globular cluster (IGC) hypothesis. They suggested three possible sources for these IGCs – cooling flows, local density enhancements and tidal stripping. Cooling flow GC formation has been discussed above. Even if a mechanism could create GCs in local density enhancements outside of galaxies, it would not account for the known correlations of GCs with their parent galaxy (e.g. the GC metallicity–galaxy luminosity relation). Tidally stripped GCs may be more viable, especially in light of the recent discoveries of intergalactic planetary nebulae (Theuns & Warren 1997). This is however unlikely to be the source of the entire  $\sim 10,000$  excess GCs required in high  $S_N$  galaxies and metallicity is still an important constraint. We further discuss tidal stripping below.

### 3.4. In Situ Formation

Harris and co-workers (e.g. Harris 1991; McLaughlin *et al.* 1994; Harris, Pritchet & McClure 1995; Durrell *et al.* 1996) advocate *in situ* formation for *most* of the GCs in gE and cD galaxies, with possibly a small contribution from other sources. Durrell *et al.* (1996) found that GCs with  $M \geq 10^5 M_\odot$  have a power-law mass distribution of the same form, which is remarkably independent of galaxy type, luminosity and environment. This suggests a similar GC formation mechanism for all galaxies, including dwarfs, giants and cD galaxies. The power-law is identical to that for giant molecular clouds (GMCs) in our Galaxy. In a study of the currently

merging galaxy NGC 3921, Schweizer *et al.* (1996) concluded that GMCs are associated with the formation of protoglobular clusters. The largest GMCs may have similar masses and densities to the primordial fragments proposed by Searle & Zinn (1978) as the building blocks of galaxies (see also Harris & Pudritz 1994). In this case a dwarf elliptical may represent a few Searle–Zinn fragments whereas large galaxies are made up of numerous such fragments.

For cD galaxies, an argument in favor of *in situ* formation is that with a GC formation efficiency of  $\leq 1\%$  (Ashman & Zepf 1992; Larson 1993) about  $10^{11} M_\odot$  of gas would be required to form the ‘excess’  $\sim 10,000$  GCs seen (assuming each GC has a mass of  $10^5 M_\odot$ ). Thus apparently most of the GCs in cD galaxies were formed at an early epoch when the galaxy itself was in a mostly gaseous phase. In early-type galaxies, the observations that GCs are more metal-poor in the mean than the underlying starlight at a given radius and that the GC systems tend to be more spatially extended than the starlight suggest that the GCs formed before the bulk of the galaxy field stars (Harris 1991). The various known correlations between the GC system and the parent galaxy suggest that the epoch of this ‘pre-galaxy’ GC formation occurred just before the main collapse phase. But we now know, at least for the GC metallicity – galaxy luminosity relation (section 2.2), that the metal-poor GCs are poorly correlated, if at all, with galaxy luminosity. This relaxes the constraint on the epoch of formation for these GCs. A further modification to the standard collapse picture is required to explain the presence of two distinct GCs populations (as indicated by the now well-established bimodal color distributions) which rules out a simple monolithic

collapse. Below we discuss our view for GC formation in a multiphase collapse.

At early times, low-metallicity pre-galaxy GCs and some field stars will form, enriching the protogalactic gas. If only a small fraction of the total gas is used in this initial phase, then the remaining metal-enriched gas should undergo further collapse. A second episode of star formation is required to produce the metal-rich GCs. In this ‘galaxy’ phase the vast majority of field stars also form. Such episodic formation in different metallicity gas could be expected to give rise to bimodal GC metallicity distributions. We would expect the pre-galaxy GCs to have a nearly spherical distribution, show little or no rotation and have a large velocity dispersion. There is some evidence to support this prediction. Grillmair *et al.* (1994b) found that a sample of GCs in the outer regions of NGC 1399 (which would be dominated by the metal-poor ones) had a much higher velocity dispersion than the stars in the main body of NGC 1399 and with no measurable rotation. In NGC 4486, GCs also have higher velocity dispersions than the galaxy stars in the outer regions (Huchra & Brodie 1987; Mould *et al.* 1990). The metal-rich GCs formed in the second (galaxy) phase may show some rotation depending on the degree of dissipation during the collapse and the presence of torques.

We also expect the pre-galaxy GCs to have a high  $S_N$  value associated with them as very few field stars form in the initial phase. Thus high  $S_N$  galaxies may simply be those with a higher fraction of pre-galaxy (metal-poor) GCs. Some evidence to support this idea is shown in Fig. 3 which shows that high  $S_N$  galaxies have relatively more metal-poor GCs than metal-rich ones. The physical mechanism for regulating the number of pre-galaxy

GCs may depend on local density. In general the star formation time scale varies as  $\propto \rho^{-1}$ , whereas the dynamical collapse time varies as  $\propto \rho^{-1/2}$ . So if the local ambient density is high, a larger fraction of the initial material turns into GCs leaving less gas for the second episode of GC formation. High  $S_N$  galaxies could simply be those with more locally dense and/or clumpy gas. Another possibility, is that the number of pre-galaxy GCs depends on the total mass of the protogalactic cloud. However we do not find a strong trend for the number of metal-poor GCs (see Table 1) to scale with galaxy luminosity, suggesting that the mass of the protocloud is not a major factor.

Perhaps the main problem with this collapse picture is the lack of a well-understood mechanism for initiating GC (and star) formation in the pre-galaxy phase, turning it off and turning it on again at some later stage in the collapse. Recently, Burkert & Ruiz-Lapuente (1997) have proposed a model in which, after the first star formation phase, subsequent star formation may be stalled by several Gyrs. They propose that the hot gas initially heated by SNe type II in the first phase, will only partially cool before being reheated by SNe type Ia. This re-heating delays the second star formation phase. Their model was applied to small galaxies; it would be very interesting if it could be extended to include large galaxies. It is interesting that the metallicity difference between the two GC populations is about 1 dex in  $[\text{Fe}/\text{H}]$  for most large galaxies. If confirmed by larger samples, this would suggest some underlying uniformity in the formation process and the length of the dormant phase. If we crudely assume that all large galaxies have metal-poor GCs with a mean of  $[\text{Fe}/\text{H}] = -1.2$  and metal-rich ones

with a mean of  $[\text{Fe}/\text{H}] = -0.2$ , then the age-metallicity relation for Milky Way halo GCs (Chaboyer *et al.* 1992) indicates that the metal-rich GCs formed  $\sim 4$  Gyrs after the metal-poor ones. Some evidence for early star formation followed by an extended dormant phase comes from a recent study of the Local Group Carina galaxy by Smecker-Hane *et al.* (1996). In this case the first epoch of star formation occurred about 12 Gyrs ago and the second phase  $\sim 5$  Gyrs later.

In the Milky Way, and by inference spiral galaxies in general, there are two distinct populations of GCs associated with the disk and halo components. With reference to the collapse picture above, the halo GCs have kinematics and metallicities similar to those of halo stars (Carney 1993). This indicates that halo stars and GCs were formed in the halo at much the same time, and may therefore be the spiral galaxy analog to the metal-rich GC population in ellipticals. We speculate that the disk GCs in spirals represent a third stage of the collapse process (which is absent in gE galaxies).

### 3.5. Tidal Stripping

The transfer of GCs from small galaxies to a high  $S_N$  galaxy by tidal stripping has been suggested by several authors and discussed by van den Bergh (1990). For example, Forte *et al.* (1982) proposed that NGC 4486 (M87) had captured a significant number of GCs from other Virgo cluster galaxies. The exchange of GCs between galaxies has been modeled in a simple way by Muzzio and collaborators (e.g. Muzzio *et al.* 1984; Muzzio 1987). The main argument put forward against this hypothesis is that GCs and starlight will be removed in the same proportions so that, although the total number of

GCs is increased, the  $S_N$  value is unaffected (van den Bergh 1984; Harris 1991). However there is an important point to be made. The GCs in at least some galaxies tend to be more extended radially than the underlying starlight so that the local  $S_N$  value increases with galactocentric radius (e.g. Forbes *et al.* 1996). In the case of NGC 4472, the global  $S_N$  is 5.5 whereas the local  $S_N$  exceeds 30 at 90 kpc (McLaughlin *et al.* 1994). Thus GCs tidally stripped from the outer parts of a galaxy may have a high  $S_N$  value, similar to that of the cD envelope of M87 ( $S_N \sim 25$ ). Tidal effects would, in their weakest form, remove only the outermost GCs and if strong enough, the whole galaxy could be accreted by its more massive neighbor. Fully-accreted galaxies will have their orbital energy converted into internal heat, which acts to ‘puff-up’ the outer envelope of the primary galaxy (Hausman & Ostriker 1978).

In Table 3 we list three nearby galaxies that may have undergone a tidal interaction with their more massive neighbors. They are: NGC 1404 (E1) located near NGC 1399 in Fornax; NGC 4486B (cE0) near NGC 4486 in Virgo and NGC 5846A (cE2) near NGC 5846 in a compact group. Faber (1973) suggested that the two compact ellipticals were actually tightly bound cores of tidally stripped galaxies. This idea is supported by the simulations of Agulier & White (1986) who show that tidal interaction results in a more compact secondary galaxy. As the central velocity dispersion is largely unaffected by tidal stripping we can estimate the original luminosity of the companion galaxy from the  $L-\sigma$  scaling relation of normal ellipticals (e.g. Faber *et al.* 1996). Furthermore using the GC metallicity-luminosity relation from Forbes *et al.* (1996) we can estimate the mean metal-

licity of the tidally stripped GCs. The predicted original luminosity of the galaxy and GC metallicity, along with estimates of the uncertainty, are given in Table 3. The predicted luminosity, suggests that NGC 4486B has lost about  $\sim 95\%$  of its stars and NGC 5846A  $\sim 70\%$ . On the other hand, NGC 1404 has an observed luminosity that is consistent with its velocity dispersion, suggesting that if tidal stripping has occurred it has removed very little galaxy starlight (but it may still have stripped off outer GCs).

If some fraction of the GC system of the companion galaxies has been removed via tidal stripping, then perhaps these GCs can be identified by their metallicity in the more massive galaxy. Figure 5 shows the metallicity distribution of GCs in NGC 1399, 4486 and 5846. We also show the predicted metallicities of the acquired GCs (as listed in Table 3) from the companion galaxies, i.e. NGC 1404, NGC 4486B and NGC 5846A respectively.

For NGC 1404 the predicted GC mean metallicity is  $[\text{Fe}/\text{H}] = -0.7 \pm 0.3$ . Estimates of the number of GCs in NGC 1404 have been made by Richtler *et al.* (1992) and Hanes & Harris (1986) from ground-based studies. For a distance modulus of 31.0, they found  $N_{GC} = 880 \pm 120$  ( $S_N = 3.2 \pm 0.4$ ) and  $N_{GC} = 190 \pm 80$  ( $S_N = 0.7 \pm 0.3$ ) respectively. Most recently Forbes *et al.* (1997), using HST data, calculated the number to be  $N_{GC} = 620 \pm 130$  ( $S_N = 2.3 \pm 0.4$ ). The Forbes *et al.* (1997) data had the advantages over ground-based studies of very low contamination rates from foreground stars and background galaxies, a background field and a pointing  $\sim 10$  arcmin from NGC 1399 on the opposite side to NGC 1404 (allowing subtraction of GCs associated with NGC 1399). We believe that

the HST data offers a more reliable estimate of the number of GCs and we will adopt this value (as given in Table 1) which is close to the weighted average of the two ground-based studies. If we assume that NGC 1404 once had a ‘normal’ GC population with  $S_N = 5 \pm 1$ , then we can estimate the number of missing GCs. Thus:

$$N_{\text{missing}} = 5 \times 10^{-0.4(M_V + 15)} - N_{\text{now}}$$

For  $M_V = -21.08$ , we estimate that NGC 1404 had an original GC population of  $1350 \pm 270$ . So NGC 1404 may have lost  $\sim 730$  GCs with a mean metallicity of  $[\text{Fe}/\text{H}] = -0.7 \pm 0.3$ . On the otherhand, NGC 1399 reveals an intermediate metallicity peak at  $[\text{Fe}/\text{H}] \sim -0.8$  (Ostrov *et al.* 1993), as shown in Fig. 5. The number of GCs with this intermediate metallicity is estimated to be 40% of the total number of GCs (see Table 1), i.e. about  $2100 \pm 700$ . It is plausible that a large fraction of the intermediate metallicity population GCs in NGC 1399 have been tidally stripped from NGC 1404. This possibility is explored further in section 4 below.

The GC metallicity distribution in NGC 4486, from Washington photometry, is claimed to have three peaks at  $[\text{Fe}/\text{H}] = -1.35, -0.8$  and  $-0.1$  (Lee & Geisler 1993). However, we note that central (Whitmore *et al.* 1995) and slightly off-center (Elson & Santiago 1996) HST images reveal only the metal-poor and metal-rich peaks from V-I colors. Geisler *et al.* (1996) discussed this possible contradiction and suggested that it could be due to the different radial samplings of the three studies. Whatever the explanation, the presence of an intermediate metallicity population is not crucial to our analysis, only that there exist some fraction of GCs with  $[\text{Fe}/\text{H}] \sim -$

0.8, which in turn could be those stripped from NGC 4486B. The predicted mean metallicity of the stripped GCs from NGC 4486B is  $[\text{Fe}/\text{H}] = -0.7 \pm 0.3$ . The total number of GCs in the NGC 4486 system is  $13,000 \pm 500$  (Harris 1996). We estimate from the data of Lee & Geisler (1993) that the fraction of GCs at this intermediate metallicity is about 40% or  $5200 \pm 200$ . For a normal  $S_N$  value of  $5 \pm 1$  and  $M_V = -21.0$  we would expect NGC 4486B to have an original population of  $1250 \pm 250$  GCs. Thus NGC 4486B has not contributed significantly to the overall GC system in NGC 4486 but may represent some fraction of the intermediate metallicity GCs. Other galaxies may have also contributed GCs to NGC 4486.

The GC metallicity distribution in NGC 5846 has two broad peaks, the metal-poor peak ranging from  $-1.3 < [\text{Fe}/\text{H}] < -0.9$  (Forbes, Brodie & Huchra 1997). The metallicity of NGC 5846A GCs, predicted from its original luminosity, is  $[\text{Fe}/\text{H}] = -0.8 \pm 0.3$ . The total number of GCs in NGC 5846 is estimated to be  $3120 \pm 1850$  (Harris 1996). We note that Forbes, Brodie & Huchra (1997) estimate a total of  $4670 \pm 1270$  from HST imaging. Using the Harris value, there are about  $780 \pm 463$  metal-poor GCs. This compares with  $800 \pm 150$  GCs as the estimate of the original GC population in NGC 5846A. Thus tidally stripped GCs from NGC 5846A may have contributed to the metal-poor peak in NGC 5846.

Blakeslee (1996) found a correlation of  $S_N$  with local galaxy density for cluster galaxies, and noted that this can be understood in the context of tidal stripping. As the crossing time in high velocity dispersion clusters is shorter, individual galaxies can pass close to the cluster center many times, increasing the occurrence of interactions accordingly.

#### 4. A Case Study: The Fornax Cluster

The Fornax cluster of galaxies is a good region in which to search for the effects of tidal stripping. The cluster itself is relatively nearby at 16 Mpc and well-studied. Furthermore it is more compact and perhaps dynamically older than the Virgo cluster. A sketch of the inner regions of the Fornax cluster is shown in Fig. 6. The cD galaxy, NGC 1399, is centered in the cluster X-ray emission which extends out to at least  $38'$  or 175 kpc (Ikebe *et al.* 1996). The nearby elliptical NGC 1404 lies within the X-ray envelope of NGC 1399 and appears to have an abnormally low  $S_N$  value of  $2.3 \pm 0.4$ . In section 4.5 we noted that NGC 1404 may have been tidally stripped of GCs, which have since been acquired by NGC 1399 which has  $S_N = 13 \pm 4$ .

Following the arguments of Faber (1973) we can make a crude estimate of the tidal radius in NGC 1404, i.e. the radius beyond which material has been tidally stripped by NGC 1399. The tidal radius  $R$  in kpc is given by:

$$R = D(3.5M_1/M_2)^{-1/3}$$

where  $D$  is the distance of closest approach, and the masses of NGC 1399 and NGC 1404 are denoted by  $M_1$  and  $M_2$  respectively. We will assume that  $D$  is equal to the current projected separation of  $9.7'$  or 45 kpc (note that the orbital pericenter may be somewhat smaller, and that the current physical separation is quite probably larger than 45 kpc). For  $M_V = -21.45$  and  $-21.08$ ,  $L_V = 3.2$  and  $2.3 \times 10^{10} L_\odot$  for NGC 1399 and NGC 1404 respectively. If both galaxies have the same M/L ratio then the tidal radius  $R = 15$  kpc. There



is evidence from X-ray observations and GC kinematics that  $M/L \sim 50\text{--}100 M_\odot/L_\odot$  for NGC 1399 (Grillmair *et al.* 1994b). If NGC 1399 has a  $M/L$  some 10–20 times that of NGC 1404, then the tidal radius becomes  $R \sim 10$  kpc. Richtler *et al.* (1992) and Forbes *et al.* (1997) estimate that the GC system of NGC 1404 terminates at a galactocentric distance of about 18 kpc. This radius is similar to that estimated above and suggests that tidal stripping of the outer GCs is a plausible mechanism to explain the absence of GCs beyond 18 kpc.

Globular cluster velocity dispersions also appear to match the expectations from the tidal stripping hypothesis. Grillmair *et al.* (1994b) found that a sample of 50 GCs in NGC 1399 (with a mean galactocentric radius  $\sim 40$  kpc) had a velocity dispersion of nearly  $400 \text{ km s}^{-1}$ . This value is much higher than the *stellar* velocity dispersion measured in NGC 1399 at somewhat smaller radii, but is similar to the velocity dispersion measured for galaxies of the Fornax cluster. The similarities in velocity dispersions of GCs and Fornax galaxies is naturally consistent with a tidal stripping scenario within the dark matter halo of NGC 1399, since the material stripped from a passing or infalling galaxy will retain most or all of the specific angular momentum (with respect to NGC 1399) of its parent galaxy. Arnaboldi *et al.* (1994) find a remarkably similar velocity dispersion among the planetary nebulae at distances  $\sim 25$  kpc, increasing confidence in the GC result and lending support to the idea that tidal stripping contributes to both the GC system and stellar envelope of cD galaxies.

Have any other galaxies, besides NGC 1404, in the Fornax cluster been tidally stripped of GCs which may also contribute to the GC sys-

tem of NGC 1399 ? The GC systems of several Fornax cluster galaxies have been studied recently by Kissler-Patig *et al.* (1996). Using  $(m-M) = 31.0$ , V band magnitudes from Faber *et al.* (1989) and  $N_{GC}$  from Kissler-Patig *et al.* we list their  $S_N$  values, luminosities, predicted mean GC metallicities and projected distances from NGC 1399 in Table 4. Table 4 seems to indicate that  $S_N$  increases with distance from the cluster center, although the formal errors are consistent with a constant  $S_N$  value. Nevertheless the trend with projected distance may indicate that several Fornax galaxies have undergone some tidal stripping.

Further evidence for tidal stripping comes from a comparison of the GC surface density slope and that of the underlying starlight. Initially a GC system may be more extended than the starlight with a flatter slope, tidal stripping will tend to remove the outermost GCs so that the GC system becomes truncated and the GC surface density slope may approach that of the stellar profile. Fig. 2 shows that low to normal  $S_N$  galaxies have a wide range of GC radial slopes and presumably a wide range in the difference between GC and starlight radial profiles. Kissler-Patig *et al.* (1996) have measured the radial slopes for NGC 1399 and four other Fornax galaxies. The latter galaxies (NGC 1427, 1374, 1379 and 1387) have GC slopes that are the same as the underlying starlight within the errors, whereas NGC 1399, has a GC slope that is noticeably flatter than the starlight.

In the context of the above discussion, there are many similarities between the Fornax cluster and the Virgo cluster. In Virgo, the central cD (NGC 4486) is also embedded within an extensive X-ray envelope. The GCs in the outer regions have a higher mean veloc-

ity dispersion than the galaxy stars (Huchra & Brodie 1987; Mould *et al.* 1990). However, there are also some notable differences between NGC 4486 (M87) and NGC 1399. NGC 4486 has far fewer near neighboring galaxies and a much smaller cD envelope than NGC 1399. This combined with the higher velocity dispersion and dynamical youth of the Virgo cluster will lead to differences in the number of accreted galaxies (and their GCs) between the two cD galaxies.

## 5. Summary, Speculations and Predictions

After reviewing the current ideas on GCs in massive early-type galaxies, we have come to the conclusion that most GCs were formed *in situ* in two star formation episodes.

In cD galaxies there may be an additional contribution from GCs that have been tidally stripped from neighboring galaxies. This accreted population should have a high local  $S_N$  value and may have played an important role in the development of the cD envelope. In the cases of NGC 1399 and M87 we have identified an intermediate metallicity population of GCs that may have been acquired via tidal stripping. To a much lesser extent all galaxies are accreting small galaxies and their GCs. We discuss the Fornax cluster in some detail and suggest that several galaxies near the central cD (NGC 1399) may have been tidally stripped of GCs. Evidence for this includes currently low  $S_N$  values, steep GC radial distributions that match the starlight and the high velocity dispersion in the outer NGC 1399 GCs.

The gaseous merger model for GC formation (Ashman & Zepf 1992), although generally consistent with currently merging galaxies, does not adequately explain the observa-

tional data for GCs in the massive early-type galaxies. We find that the bimodal GC metallicity distributions do not match the merger model expectations when examined in detail. In particular, *the GC systems of high  $S_N$  galaxies do not have more metal-rich GCs as would be expected in the merger model but instead have more metal-poor ones.* This means that GC metallicity gradients are steeper in high  $S_N$  galaxies, contrary to the predictions of Ashman & Zepf (1992).

We favor an early collapse picture for galaxy formation (see for example Eggen, Lynden-Bell & Sandage 1962; Larson 1975; Gott 1977; Sandage 1990) that probably involves some chaotic merging of many small subunits (Searle & Zinn 1978; Katz 1992). We speculate that there are three main phases in the collapse process (which we call pre-galaxy, galaxy and disk phases) each of which may have associated GC formation. First, in the early stages of the collapse, there occurs rapid star formation. Only a small fraction of the available gas is converted into stars, and most of these stars are located in GCs which formed from the chaotic merging of dense, gravitationally bound clumps. These GCs have a high velocity dispersion, are distributed throughout the cloud volume and are metal-poor. The ratio of stars in GCs to field stars is large (i.e. the specific frequency is high). There will be little or no radial abundance gradient in the GC system from this phase. Both the field stars and GCs provide enrichment for the remaining gas. In the second phase, after the gas cloud has undergone further collapse, field star formation is preferred over star formation in GCs (possibly due to more efficient cooling at higher metallicities). Both field stars and GCs will have essentially the same metallicity (i.e. relatively

metal-rich). They will have some rotation depending on the degree of dissipation in the collapse. Unconsumed gas will eventually settle into a disk-like structure near the galaxy center. Thus the small disks (e.g. Scorza & Bender 1996) and peaky stellar distributions (e.g. Forbes, Franx & Illingworth 1995) seen in low luminosity ellipticals may indicate a prolonged dissipative collapse in the less massive systems. The variation of galaxy properties from large to small ellipticals may reflect a sequence of decreasing gas-to-star conversion efficiency (see also Bender, Burstein & Faber 1992). We note that the main difficulty with this scenario is the lack of detailed mechanism for creating two distinct phases of GC formation from a single halo collapse.

Spiral galaxies may represent the extreme of this process with very inefficient conversion of gas into stars. Spirals will have virtually no pre-galaxy star formation, so that the enrichment levels of the second phase of collapse are reduced leading to GCs that are in general more metal-poor (i.e.  $[\text{Fe}/\text{H}] \sim -1.5$ ) than the second phase GCs in ellipticals. Although they have quite different metallicities, halo GCs in spirals appear to be the analog to the metal-rich GCs in ellipticals. Spirals then go on to form a prominent disk (and associated GCs) in the third phase of the collapse. The type of the final galaxy produced by the above process will depend largely on the initial conditions of the the protogalactic gas cloud. For example, protoellipticals may be more dense, more clumpy and more chaotic than protospirals. As the ambient density and clumpiness of the protoelliptical increases, more metal-poor GCs with a high  $S_N$  value are produced. At the extreme end of this process, and when the protoelliptical is located close to the gravitational center of

a galaxy cluster, a cD galaxy is formed.

We conclude that episodic *in situ* GC formation and a contribution from accretion/tidal stripping in the outer parts of cD galaxies may offer the ‘best bet’ for solving the “most outstanding problem in globular cluster system research” (McLaughlin *et al.* 1994). This origin for GCs suggests several testable predictions. They include:

- We expect the metal-poor GCs in early-type galaxies to form non-rotating, hot systems (high velocity dispersion) if their origin is either from the pre-galaxy phase or from tidal stripping. The outer (metal-poor) GCs in both NGC 1399 and NGC 4486 (M87) have high velocity dispersions. Future large samples, will hopefully be able to determine GC kinematics as a function of metallicity. The metal-poor GCs will be near spherically distributed.
- We expect the metal-rich GCs in early-type galaxies to be slowly rotating systems, with more rotation seen in low luminosity ellipticals than the giants. Some tentative evidence for GC rotation comes from Hui *et al.* (1995) who noted that the metal-rich GCs in NGC 5128 appeared to share the rotation properties of the system of planetary nebulae. The metal-rich GCs will closely match the ellipticity of the underlying galaxy.
- We have found that the metallicity of the metal-rich GC population is more closely coupled to parent galaxy luminosity than the metal-poor population. This suggests that the GC mean metallicity – galaxy luminosity relation is driven by the metal-rich population, and galaxies with a significant metal-poor population (i.e. the high  $S_N$  galaxies)

will lie below the mean relation, to lower metallicity, for a given luminosity.

- As more bimodal GC systems are discovered in ellipticals, we predict that they will follow the current trends of proportionately more metal-poor GCs and steepening radial metallicity gradients with increasing specific frequency.

- We expect low luminosity, low  $S_N$  elliptical galaxies to have relatively more metal-rich than metal-poor GCs. Given the smaller number of GCs present (and an even smaller population of metal-poor ones, if present at all) it may be very difficult to detect a bimodal metallicity distribution. We predict that many ellipticals, without obvious bimodality, will have metallicity (color) distributions that are intrinsically broad, i.e. broader than the photometric or spectroscopic measurement errors.

- Tidally stripped galaxies may have steeper GC radial surface density slopes than non-stripped galaxies. Some initial support for this prediction comes from Fleming *et al.* (1995) who finds that galaxies in clusters have steeper GC radial slopes, at a given magnitude, than those in low density environments. The study of Fornax cluster galaxies by Kissler-Patig *et al.* (1996) also supports this prediction.

- Tidally stripped galaxies will have lower than average  $S_N$  values, i.e.  $\leq 5$ . In the case of NGC 4486B and NGC 5846A we suggest that the vast majority of GCs and field stars have been removed by tidal interaction with their more massive neighbor, and we expect  $S_N \sim 1$  for these two compact ellipticals.

## Acknowledgments

We thank R. Elson, W. Harris, M. Kissler-Patig, B. Whitmore, A. Zabludoff and S. Zepf for useful discussions and comments. We also thank the referee, S. van den Bergh, for his careful reading and suggestions for improving the paper. This research was funded by the HST grant GO-05920.01-94A and GO-05990.01-94A

## References

- Arnaboldi, M. *et al.* 1994, ESO Messenger, 76, 40  
 Ashman, K. M., & Bird, C. M. 1993, AJ, 106, 2281  
 Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50  
 Ashman, K. M., & Zepf, S. E. 1997, Globular Cluster Systems, (Cambridge University Press, Cambridge), in press  
 Aguiar, L., & White, S. D. M. 1986, ApJ, 307, 97  
 Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462  
 Blakeslee, J. P. 1996, Ph.D. Thesis, MIT  
 Bridges, T. A., Carter, D., Harris, W. E., & Pritchett, C. J. 1996a, MNRAS, 281, 1290  
 Bridges, T. A., Carter, D., Zepf, S. E., Ashman, K. M., Hanes, D. A., & Dow, P. 1996b, Spectrum, 9, 8  
 Brodie, J. P., & Huchra, J. 1991, ApJ, 379, 157  
 Burkert, A., & Ruiz-Lapuente, P. 1997, ApJ, in press  
 Carollo, C. M., Franx, M., Illingworth, G. D., & Forbes, D. A. 1997, ApJ, in press  
 Carney, B. 1993, The Globular Cluster – Galaxy Connection, ed. G. Smith and J. Brodie, (ASP conference series, San Francisco), p. 234  
 Chaboyer, B., Sarajedini, A., & Demarque, P. 1992, ApJ, 394, 515  
 Durrell, P. R., Harris, W. E., Geisler, D., & Pudritz, R. E. 1996, AJ, 112, 972  
 Eggen, O. J., Lynden-Bell, D., & Sandage, A. 1962, ApJ, 136, 748  
 Elson, R. A. W., & Santiago, B. X. 1996, MNRAS, 280, 971  
 Faber, S. M. 1973, ApJ, 179, 423  
 Faber, S. M., *et al.* 1989, ApJS, 69, 763  
 Faber, S. M., *et al.* 1996, preprint  
 Fabian, A. C., Nulsen, P. E. J., Canizares, C. R. 1984, Nature, 310, 733  
 Fall, S. M., & Rees, M. J. 1985, ApJ, 298, 18  
 Fall, S. M., & Rees, M. J. 1988, in Globular Cluster Systems in Galaxies, edited by J. Grindlay and A. Philip (Reidel, Dordrecht), p. 323  
 Fleming, D. E. B., Harris, W. E., Pritchett, C. J., & Hanes, D. A. 1995, AJ, 109, 1044  
 Forbes, D. A., Brodie, J. P., & Huchra, J. 1996, AJ, 112, 2448  
 Forbes, D. A., Brodie, J. P., & Huchra, J. 1997, AJ, in press  
 Forbes, D. A., Franx, M., & Illingworth, G. D. 1995, AJ, 109, 1988  
 Forbes, D. A., Franx, M., Illingworth, G. D., & Carollo, C. M. 1996, ApJ, 467, 126  
 Forbes, D. A. *et al.* 1997, in preparation  
 Forte, J. C., Martinez, R. E., & Muzzio, J. C. 1982, 87, 1465  
 Geisler, D., Lee, M. G., & Kim, E. 1996, AJ, in press  
 Gott, J. R. 1977, ARAA, 29, 299  
 Grillmair, C., Pritchett, C., & van den Bergh, S. 1986, AJ, 91, 1328  
 Grillmair, C. *et al.* 1994a, AJ, 108, 102  
 Grillmair, C., *et al.* 1994b, ApJ, 422, L7  
 Hamabe, M. 1993, ApJS, 85, 249  
 Hanes, D. A., & Harris, W. E. 1986, ApJ, 309, 599  
 Harris, G. L. H., Geisler, D., Harris, H. C., & Hesser, J. E. 1992, AJ, 104, 613  
 Harris, W. E. 1991, ARAA, 29, 543  
 Harris, W. E. 1996, [www.physics.mcmaster.ca/Globular.h](http://www.physics.mcmaster.ca/Globular.h)  
 Harris, W. E., & Pudritz, R. E. 1994, 429, 177  
 Harris, W. E., & van den Bergh, S. 1981, AJ, 86, 1627  
 Harris, W. E., Pritchett, C. J., & McClure, R. D. 1995, ApJ, 441, 120  
 Hoessel, J. G., Oegerle, W. R., & Schneider, D. P. 1987, AJ, 94, 1111  
 Hausman, M. A., & Ostriker, J. P. 1978, ApJ,

- 224, 320
- Huchra, J., & Brodie, J. P. 1987, *AJ*, 93, 779
- Hui, X., Ford, H. C., Freeman, K. C., & Dopita, M. A. 1995, *ApJ*, 449, 592
- Ikebe, Y., *et al.* 1996, *Nature*, 379, 6564
- Kaisler, D., Harris, W. E., Crabtree, D. R., & Richer, H. B. 1996, *AJ*, 111, 2224
- Katz, N. 1992, *ApJ*, 391, 502
- Kissler-Patig, M. 1996, *A & A*, in press
- Kissler-Patig, M., Kohle, S., Hilker, M., Richtler, T., Infante, L., & Quintana, H. 1996, *A & A*, in press
- Kormendy, J. 1990, in *Dynamics and Interactions of Galaxies*, ed. R. Wielen (Springer-Verlag, Berlin) p. 499
- Kormendy, J., & Djorgovski, S. 1989, *ARAA*, 27, 235
- Kumai, Y., Basu, B., & Fujimoto, M. 1993a, *ApJ*, 404, 29
- Kumai, Y., Basu, B., & Fujimoto, M. 1993a, *ApJ*, 416, 576
- Larson, R. B. 1975, *MNRAS*, 173, 671
- Larson, R. B. 1993 *The Globular Cluster – Galaxy Connection*, ed. G. Smith and J. Brodie, (ASP conference series, San Francisco), p. 675
- Lauer, T., & Kormendy, J. 1986, *ApJ*, 301, L1
- Lee, M. G., & Geisler, D. 1993, *AJ*, 106, 493
- Mackie, G. 1992, *ApJ*, 400, 65
- McLaughlin, D. E., Harris, W. E., & Hanes, D. A. 1993, *ApJ*, 409, L45
- McLaughlin, D. E., Harris, W. E., & Hanes, D. A. 1994, *ApJ*, 422, 486
- Mould, J. R., Oke, J. B., De Zeeuw, P. T., & Nemec, J. M. 1990 *AJ*, 99, 1823
- Murray, S. D., & Lin, D. N. C. 1992, *ApJ*, 400, 265
- Muzzio, J. C. 1987, *PASP*, 99, 245
- Muzzio, J. C., Martinez, R. E., & Rabolli, M. 1984, *ApJ*, 285, 7
- Ostrov, P., Geisler, D., & Forte, J. C. 1993, *AJ*, 105, 1762
- Peebles, P. J. E., & Dicke, R. H. 1968, *ApJ*, 154, 891
- Richer, H. B., Crabtree, D. R., Fabian, A. C., & Lin, D. N. C. 1993, *AJ*, 105, 877
- Richtler, T., Grebel, E. K., Domgorgen, H., Hilker, M., & Kissler, M. 1992, *A & A*, 264, 25
- Sandage, A. 1990, *JRASC*, 84, 70
- Scorza, C., & Bender, R. 1996 in *New Light on Galaxy Evolution*, edited by R. Bender and R. Davies, (Kluwer, Dordrecht), p. 55
- Schweizer, F. 1987, *Nearly Normal Galaxies*, ed. S. Faber, (Springer-Verlag, New York), p. 18
- Schweizer, F., Miller, B. W., Whitmore, B. C., & Fall, S. M. 1996, *AJ*, in press
- Searle, L., & Zinn, R. 1978, *ApJ*, 225, 357
- Secker, J., Giesler, D., McLaughlin, D. E., Harris, W. E. 1995, *AJ*, 109, 1019
- Smecker-Hane, T. A., Stetson, P. B., Hesser, J. E., & VandenBergh, D. A. 1996, *From Stars to Galaxies*, ed C. Leitherer, U. Fritze von Alvensleben and J. Huchra, (ASP Conference series, San Francisco), in press
- Theuns, T., & Warren, S. J. 1997, *MNRAS*, 284, L11
- van den Bergh, S. 1975, *ARAA*, 13, 217
- van den Bergh, S. 1984, *PASP*, 96, 459
- van den Bergh, S. 1990, *Dynamics and Interactions of Galaxies*, ed. R. Wielen, (Springer-Verlag, Berlin), p. 492
- van den Bergh, S. 1995, *AJ*, 110, 2700
- Vietri, M., & Pesce, E. 1995, *ApJ*, 442, 618
- West, M. J. 1993, *MNRAS*, 265, 755
- West, M. J., Cote, P., Jones, C., Forman, W., & Marzke, R. O. 1995, *ApJ*, 453, L77
- Whitmore, B. C., Schweizer, F., Leitherer, C. Borne, K., & Robert, C. 1993, *AJ*, 106, 1354
- Whitmore, B. C., Sparks, W. B., Lucas, R. A., Macchetto, F. D., & Biretta, J. A. 1995, *ApJ*, 454, L73

Whitmore, B. C., *et al.* 1997, in preparation  
Zepf, S. E. 1996, Sant'Agata Conference on  
Interacting Galaxies, in press  
Zepf, S. E., & Ashman, K. M. 1993, MNRAS,  
264, 611  
Zepf, S. E., Ashman, K. M., & Geisler, D.  
1995, ApJ, 443, 570

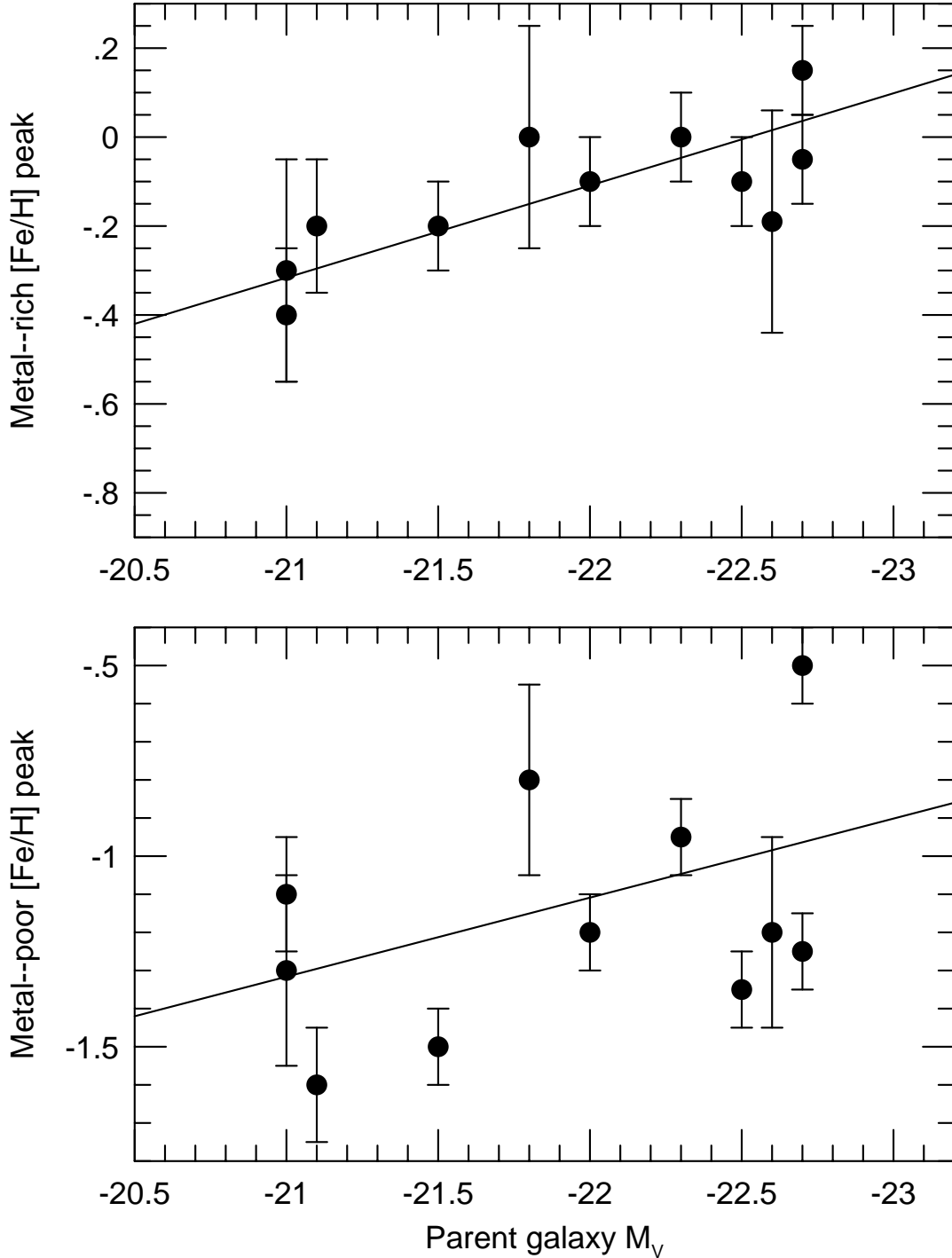


Fig. 1.— Globular cluster mean metallicity – galaxy luminosity relation. The upper panel shows the mean metallicity of the metal-rich population from Table 1. The solid line is a weighted fit to the data. A good correlation between the metallicity of the metal-rich globular clusters and the parent galaxy luminosity is present. The lower panel shows the mean metallicity of the metal-poor population. The solid line is the metal-rich relation offset lower by 1 dex in  $[Fe/H]$  (i.e the average offset between the metal-rich and metal-poor populations). There is little or no correlation between the metallicity of the metal-poor globular clusters and the parent galaxy luminosity.



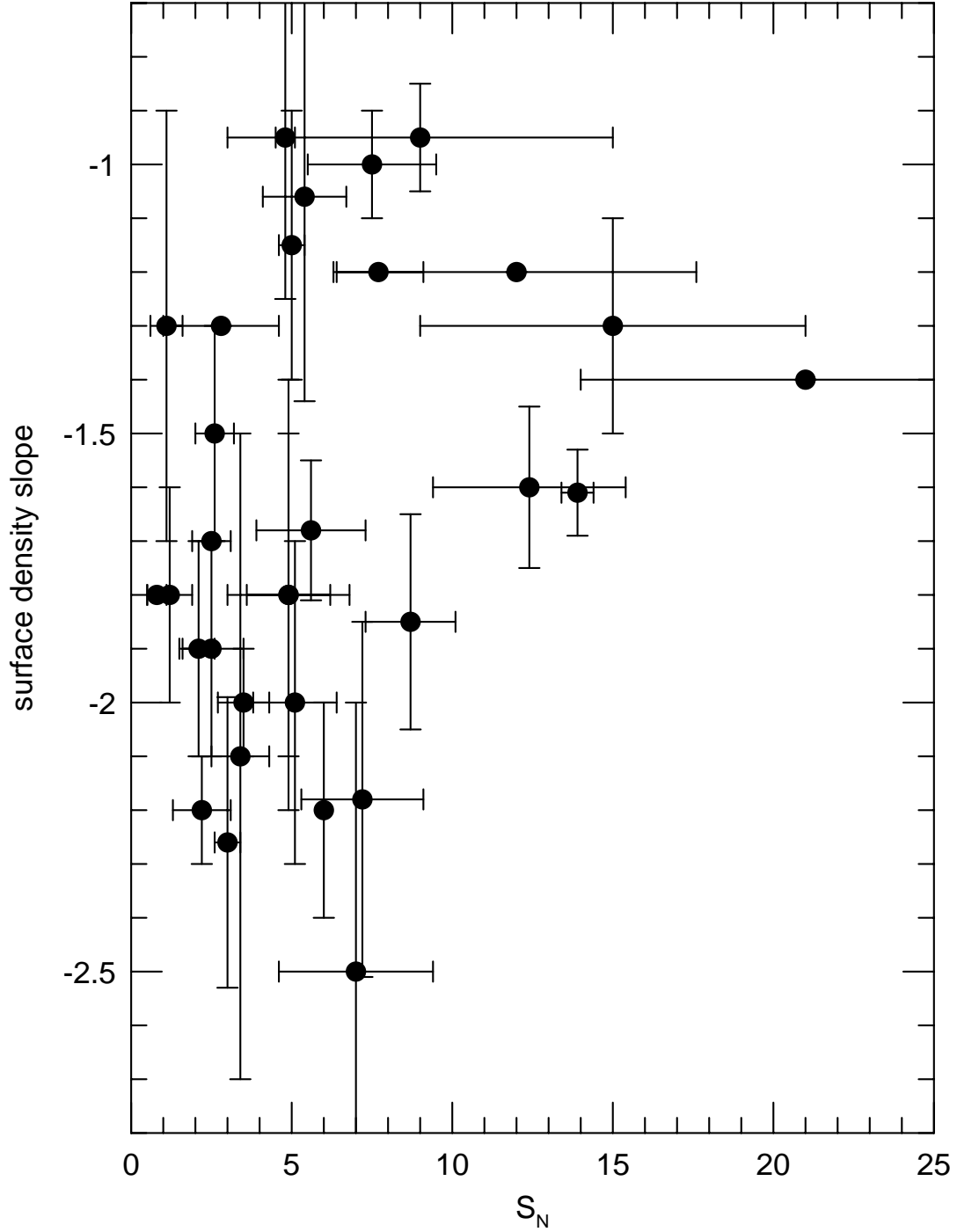


Fig. 2.— Globular cluster surface density slope versus specific frequency for elliptical galaxies. The power-law slope of the globular cluster surface density profile and the specific frequency ( $S_N$ ) are taken from the list of Kissler-Patig (1996). For low  $S_N$  galaxies there is a wide range of density slopes, but high  $S_N$  galaxies only have flat, extended globular cluster distributions.

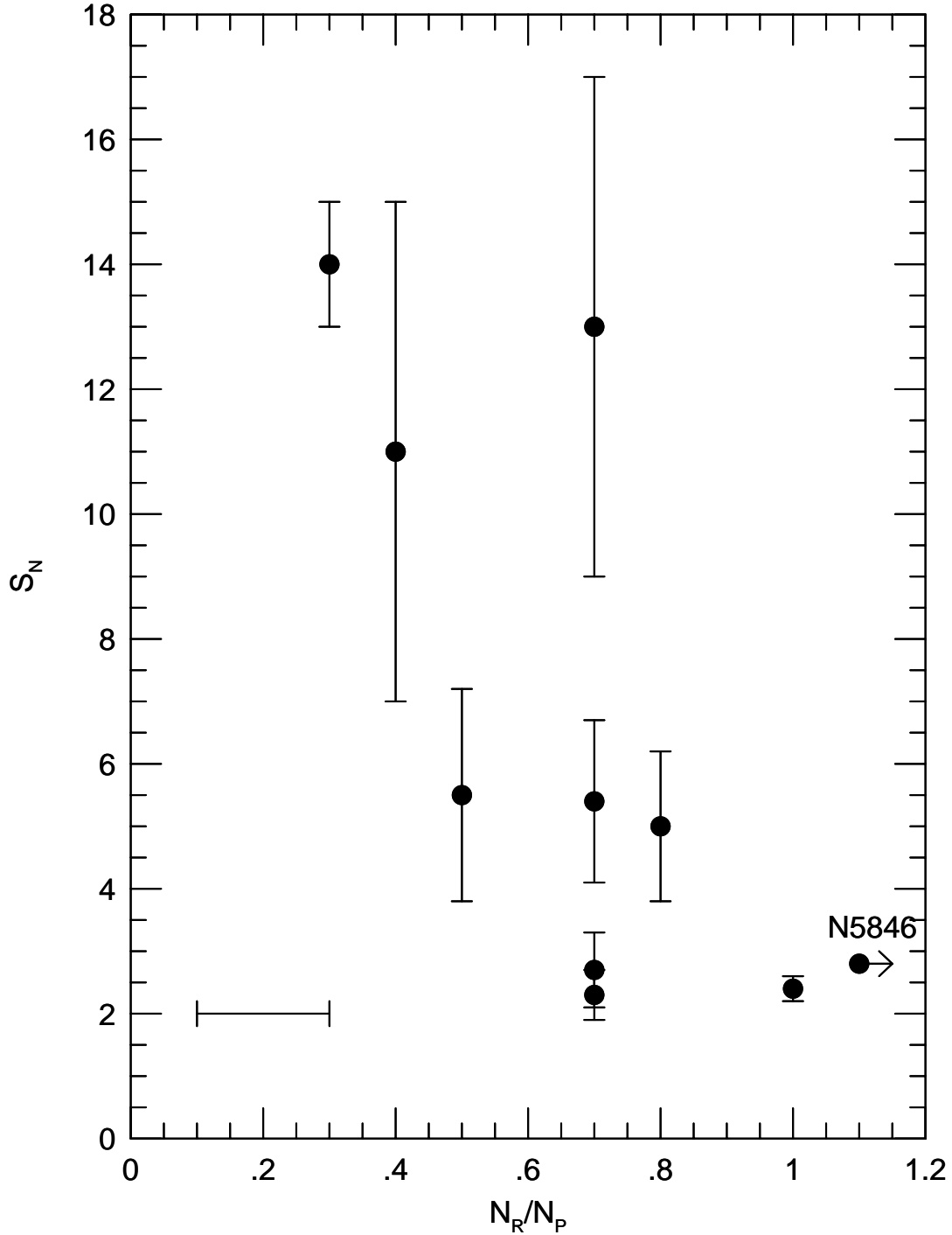


Fig. 3.— Specific frequency versus the ratio of metal-rich to metal-poor globular clusters. The data point for NGC 5846 ( $N_R/N_P = 3.0$ ,  $S_N = 2.8 \pm 1.7$ ) is not shown for display purposes. A typical error bar for  $N_R/N_P$  is shown in the lower left. The data show that as the ratio of metal-rich to metal-poor globular clusters increases the specific frequency ( $S_N$ ) value decreases. High  $S_N$  galaxies have more metal-poor globular clusters than low  $S_N$  ones. The merger model of Ashman & Zepf (1992) predicts an opposite trend to that seen i.e., an increasing  $N_R/N_P$  ratio with higher  $S_N$  values.

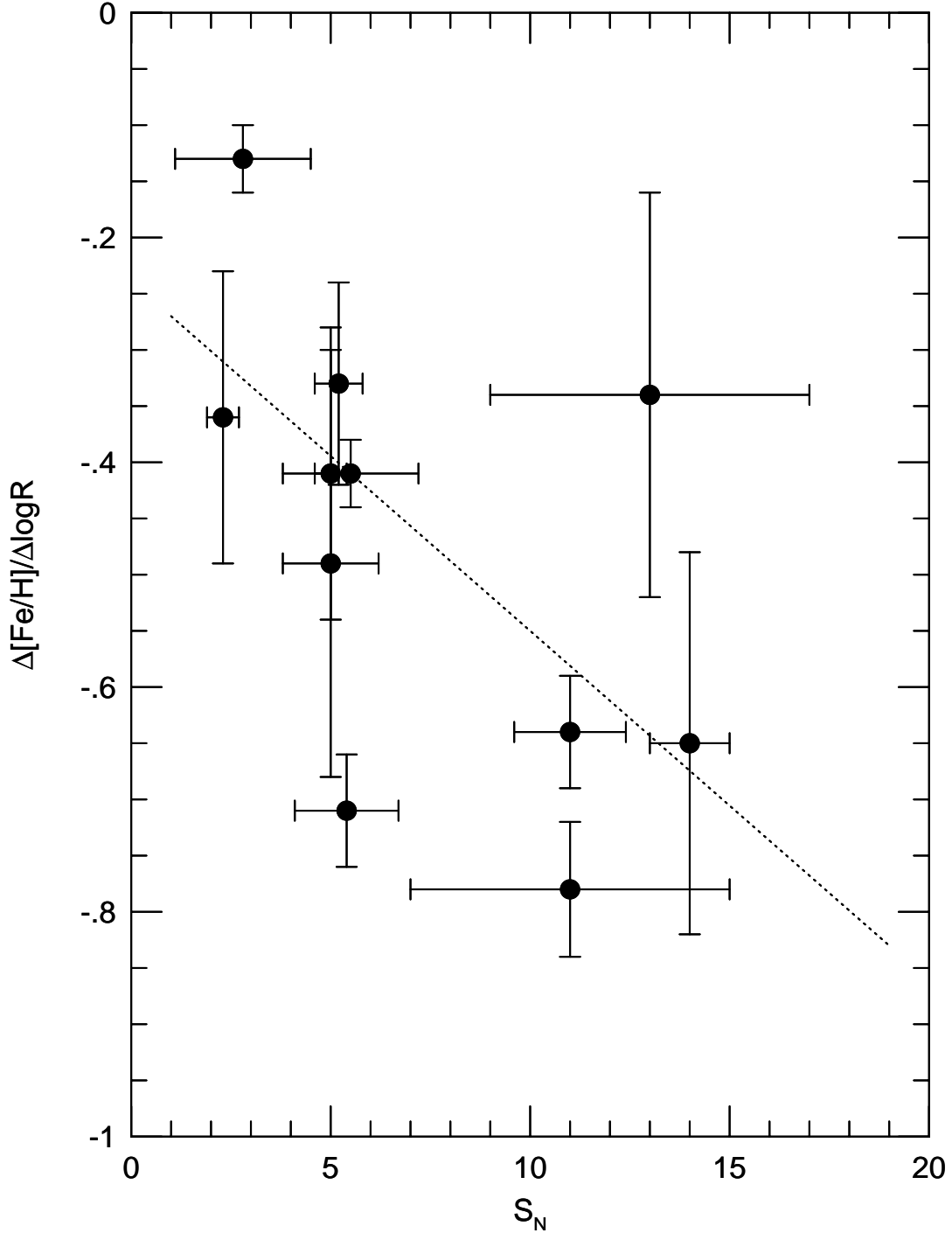


Fig. 4.— Globular cluster radial metallicity gradient versus specific frequency. The data suggest that high  $S_N$  galaxies (from Table 2) have steeper radial metallicity slopes than low  $S_N$  ones. The dashed line is the expected trend if an increase in  $S_N$  corresponds to only larger numbers of metal-poor globular clusters which are placed with the same radial distribution as seen in NGC 4472 (see text for details). The zeropoint is taken to be the current values for NGC 4472 (i.e.  $S_N = 5.5$  and  $\Delta[\text{Fe}/\text{H}]/\Delta\log R = -0.41$ ). The merger model of Ashman & Zepf (1992) predicts an opposite trend to that seen i.e., shallower metallicity gradients in high  $S_N$  galaxies.

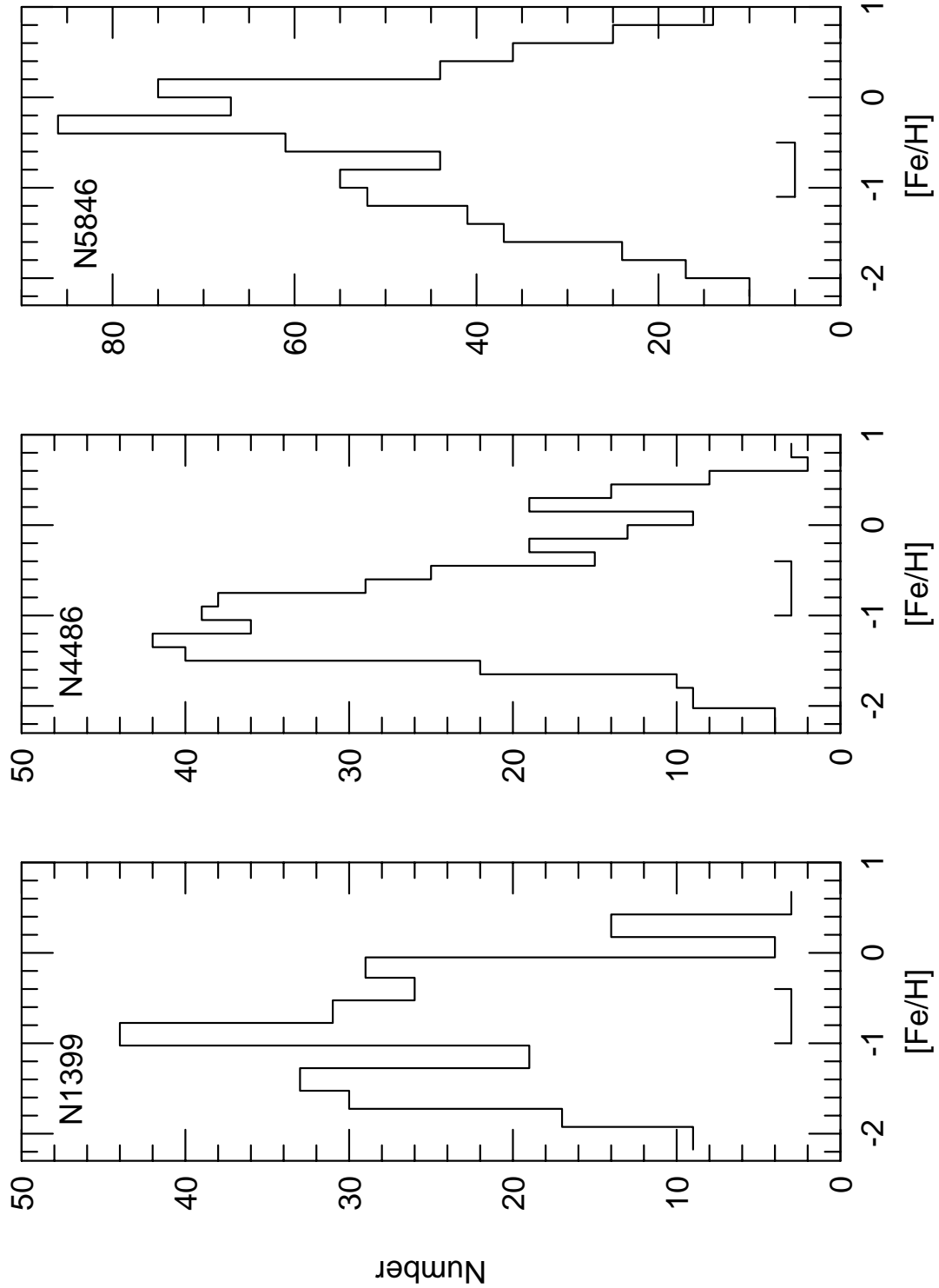


Fig. 5.— Globular cluster metallicity distribution in three central dominant galaxies. The photometric data from Ostrov *et al.* (1993) for NGC 1399, Giesler *et al.* (1996) for NGC 4486 and Forbes, Brodie & Huchra (1996) for NGC 5846 have been converted into metallicity. The expected mean metallicity of tidally stripped globular clusters from NGC 1404, NGC 4486B and NGC 5846A are marked below each distribution. In each case some of the intermediate metallicity globular clusters may have been acquired by tidal stripping.

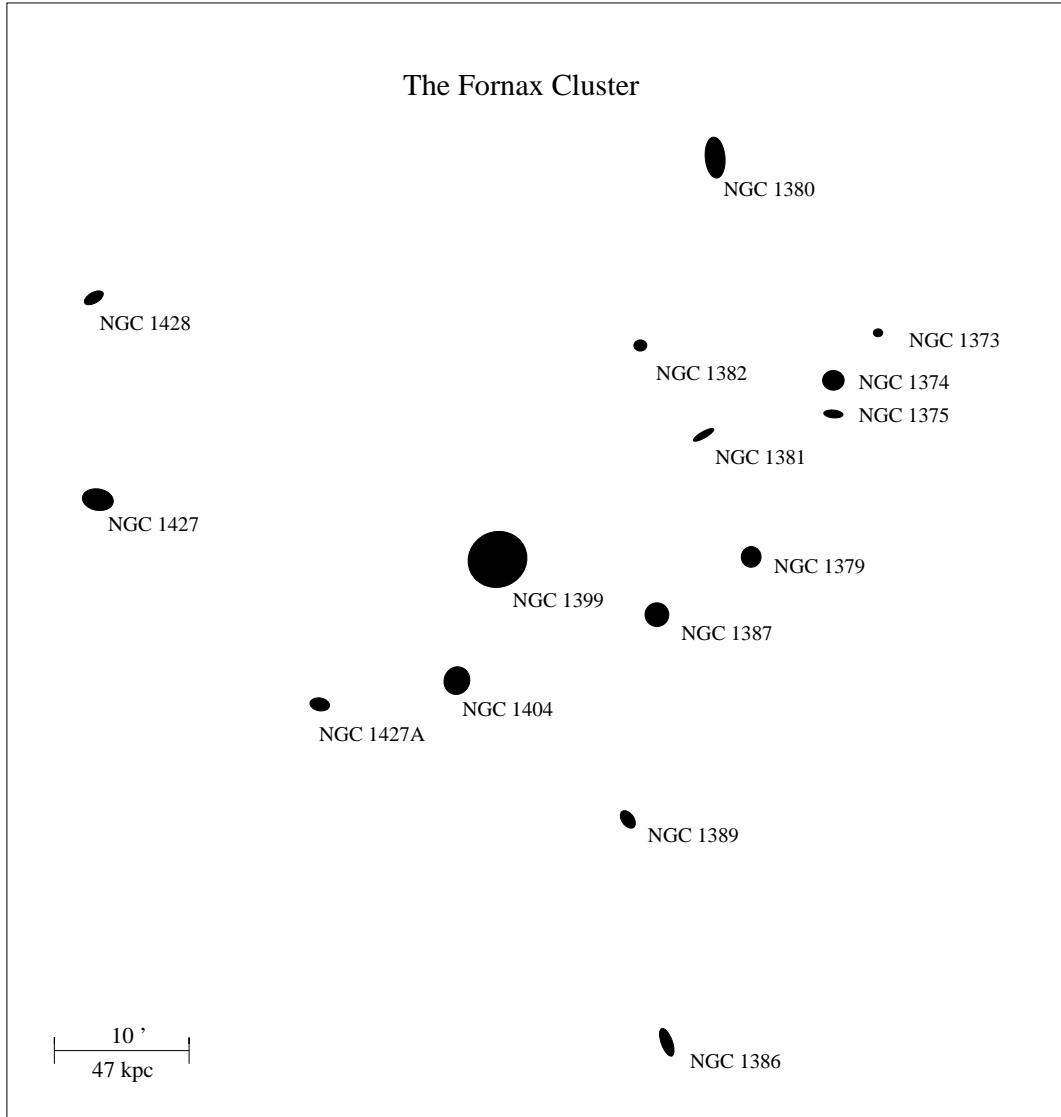


Fig. 6.— Schematic sketch of the galaxies in the central regions of the Fornax cluster. The X-ray emission extends from the cD galaxy (NGC 1399) out to at least  $38'$ .

TABLE 1. Multimodal Metallicity Distributions

Galaxy (1)	Type (2)	(m-M) (3)	$M_V$ (4)	$N_{GC}$ (5)	$S_N$ (6)	[Fe/H] (7)	Percent (8)	$N_R/N_P$ (9)	Source (10)	Ref. (11)
N1052	E4	31.3	-21.0	$600 \pm 70$	$2.4 \pm 0.2$	-1.1,-0.4	50,50	1.0	B-I	1
N1399	E1/cD	31.0	-21.5	$5340 \pm 1780$	$13 \pm 4$	-1.5,-0.8,-0.2	35,40,25	0.7	Wash	2
N1404	E1	31.0	-21.1	$620 \pm 130$	$2.3 \pm 0.4$	-1.6,-0.2	60,40	0.7	B-I	3
N3311	E0/cD	33.4	-22.7	$12400 \pm 5000$	$11 \pm 4$	-0.5,+0.15	70,30	0.4	Wash	4
N3923	E3	31.9	-22.3	$4300 \pm 1000$	$5.0 \pm 1.2$	-0.95,+0.0	55,45	0.8	Wash	5
N4472	E2	31.0	-22.7	$6300 \pm 1900$	$5.5 \pm 1.7$	-1.25,-0.05	65,35	0.5	Wash	6
N4486	E0/cD	31.0	-22.5	$13000 \pm 500$	$14 \pm 1$	-1.35,-0.75,-0.1	45,40,15	0.3	Wash	7
N4494	E0	30.8	-21.0	$1400 \pm 350$	$5.4 \pm 1.3$	-1.3,-0.3*	60,40	0.7	V-I	8
N5128	E0p	28.3	-22.0	$1700 \pm 400$	$2.7 \pm 0.6$	-1.2,-0.1	60,40	0.7	Wash	9
N5846	E0	32.3	-22.6	$3120 \pm 1850$	$2.8 \pm 1.7$	-1.2,-0.2	25,75	3.0	V-I	10
IC1459	E3	31.7	-21.8	—	—	-0.8,0.0*	70,30	0.4	V-I	8

Notes to Table 1.

(1) Galaxy name; (2) Galaxy type; (3) Distance modulus from Harris (1996); (4) Absolute V magnitude; (5) Total number of globular clusters; (6) Specific frequency; (7) Metallicity of peaks (\* indicates marginal significance); (8) Percentage of globular clusters in each peak; (9) Number of metal-rich to metal-poor globular clusters; (10) Source of metallicity (i.e. broad-band colors or Washington photometry); (11) Metallicity reference (1 Bridges *et al.* 1996b, 2 Ostrov *et al.* 1993, 3 Forbes *et al.* 1997, 4 Secker *et al.* 1995, 5 Zepf *et al.* 1995, 6 Geisler *et al.* 1996, 7 Lee & Geisler 1993, 8 Forbes *et al.* 1996, 9 Harris *et al.* 1992, 10 Forbes, Brodie & Huchra 1997).

TABLE 2. Metallicity Gradient Slopes

Galaxy (1)	(m-M) (2)	$M_V$ (3)	$S_N$ (4)	$\Delta[\text{Fe}/\text{H}]/\Delta\log R$ (5)	Ref. (6)
N1399	31.0	-21.5	$13 \pm 4$	$-0.34 \pm 0.18$	1
N1404	31.0	-21.1	$2.3 \pm 0.4$	$-0.36 \pm 0.13$	2
N3311	33.4	-22.7	$11 \pm 4$	$-0.78 \pm 0.06^*$	3
N3923	31.9	-22.3	$5.0 \pm 1.2$	$-0.49 \pm 0.19$	4
N4278	30.0	-19.9	$11 \pm 1.4$	$-0.64 \pm 0.05$	5
N4365	31.4	-21.8	$5.0 \pm 0.4$	$-0.41 \pm 0.13^\dagger$	5
N4406	31.0	-22.0	$5.2 \pm 0.6$	$-0.33 \pm 0.09$	5
N4472	31.0	-22.7	$5.5 \pm 1.7$	$-0.41 \pm 0.03$	6
N4486	31.0	-22.5	$14 \pm 1$	$-0.65 \pm 0.17$	7
N4494	30.8	-21.0	$5.4 \pm 1.3$	$-0.71 \pm 0.05$	5
N5846	32.3	-22.6	$2.8 \pm 1.7$	$-0.13 \pm 0.03$	8

Notes to Table 2.

(1) Galaxy name; (2) Distance modulus from Harris (1996); (3) Absolute V magnitude; (4) Specific frequency; (5) Globular cluster mean metallicity gradient (in dex/"). \* statistical error,  $^\dagger$  includes data from Ajhar *et al.* (1994); (6) Reference (1 Ostrov *et al.* 1993, 2 Secker *et al.* 1995, 3 Forbes *et al.* 1997, 4 Zepf *et al.* 1995, 5 Unpublished metallicity gradients using data from Forbes *et al.* 1996, 6 Geisler *et al.* 1996, 7 Lee & Geisler 1993, 8 Forbes, Brodie & Huchra 1997).

TABLE 3. Tidally Stripped Candidates

Galaxy (1)	Type (2)	(m-M) (3)	( $\Delta R$ ) (4)	( $\Delta V$ ) (5)	$M_V$ (6)	$\log \sigma$ (7)	$M_{predict}$ (8)	$[Fe/H]_{predict}$ (9)
N1404	E1	31.0	45	500	-21.1	2.353	-21.0 $\pm$ 0.5	-0.7 $\pm$ 0.3
N4486B	cE0	31.0	70	200	-17.7	2.301	-21.0 $\pm$ 0.5	-0.7 $\pm$ 0.3
N5846A	cE2	32.3	6	380	-19.2	2.230	-20.5 $\pm$ 0.5	-0.8 $\pm$ 0.3

Notes to Table 3.

(1) Galaxy name; (2) Galaxy type; (3) Distance modulus from Harris (1996); (4) Projected separation from primary in kpc; (5) Radial velocity difference from primary in  $\text{km s}^{-1}$ ; (6) Observed absolute V magnitude; (7) Central velocity dispersion; (8) Predicted V magnitude from column 7; (9) Predicted GC metallicity from column 8.

TABLE 4. Fornax Cluster Galaxies

Galaxy (1)	Type (2)	( $\Delta R$ ) (3)	$M_V$ (4)	$S_N$ (5)	$[Fe/H]_{predict}$ (6)
N1374	E1	190	-20.1	3.7 $\pm$ 0.8	-0.9 $\pm$ 0.3
N1379	E0	140	-20.3	2.4 $\pm$ 0.5	-0.8 $\pm$ 0.3
N1387	S0	85	-20.2	3.2 $\pm$ 0.9	-0.9 $\pm$ 0.3
N1404	E1	45	-21.1	2.3 $\pm$ 0.4	-0.7 $\pm$ 0.3
N1427	E3	215	-20.2	4.2 $\pm$ 0.8	-0.9 $\pm$ 0.3

Notes to Table 4.

(1) Galaxy name; (2) Galaxy type; (3) Projected separation from NGC 1399 in kpc; (4) Absolute V magnitude; (5) Specific frequency; (6) Predicted GC metallicity from column 4.